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DTRA-TR-15-34

TECHNICAL REPORT

Interaction of Radiation with Graphene Based Nanomaterials for Sensing Fissile Materials

March 2016

HDTRA1-09-1-0047

Dr. Yong P. Chen

Prepared by:
Purdue University
525 Northwestern Avenue
West Lafayette, IN 47907

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525 Northwestern Avenue
West Lafayette, IN 47907

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
We fabricated graphene on various semiconductor substrates and graphene nanocomposites with semiconductor nanoparticle fillings. We studies the transient interactions of photons (visible, X-rays and gamma rays) with graphene field effect transistors (GFET) made from exfoliated, epitaxial, and CVD graphene on various absorber substrates such as Si, SiC, and GaAs, CdTe. The potential of GFETs to sense ionizing radiation with high sensitivity, low noise, and room temperature operation has been experimentally demonstrated. We studied the photoresponse (photoconductivity) of photodectors based on graphene, graphene composite and graphene-semiconductor hybrid and achieved a high photoresponsivity at room temperature. We also investigated the long term effects of charged radiation (particular e-beam) on graphene material and its devices. Our work on the exploiting graphene-based nanostructured materials to detect ionizing radiations with high sensitivity may lead to new schemes of sensing fissle materials at long range, a major challenge in countering weapons of mass destruction (WMD).

15. SUBJECT TERMS
GFETs; graphene; semiconductor; photoconductivity

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

UNIT CONVERSION TABLE
U.S. customary units to and from international units of measurement*

U.S. Customary Units	Multiply by → / ← Divide by†		International Units
Length/Area/Volume			
inch (in)	2.54	$\times 10^{-2}$	meter (m)
foot (ft)	3.048	$\times 10^{-1}$	meter (m)
yard (yd)	9.144	$\times 10^{-1}$	meter (m)
mile (mi, international)	1.609 344	$\times 10^{3}$	meter (m)
mile (nmi, nautical, U.S.)	1.852	$\times 10^{3}$	meter (m)
barn (b)	1	$\times 10^{-28}$	square meter (m^2)
gallon (gal, U.S. liquid)	3.785 412	$\times 10^{-3}$	cubic meter (m^3)
cubic foot (ft^3)	2.831 685	$\times 10^{-2}$	cubic meter (m^3)
Mass/Density			
pound (lb)	4.535 924	$\times 10^{-1}$	kilogram (kg)
unified atomic mass unit (amu)	1.660 539	$\times 10^{-27}$	kilogram (kg)
pound-mass per cubic foot (lb ft^{-3})	1.601 846	$\times 10^{1}$	kilogram per cubic meter (kg m^{-3})
pound-force (lbf avoirdupois)	4.448 222		newton (N)
Energy/Work/Power			
electron volt (eV)	1.602 177	$\times 10^{-19}$	joule (J)
erg	1	$\times 10^{-7}$	joule (J)
kiloton (kt) (TNT equivalent)	4.184	$\times 10^{12}$	joule (J)
British thermal unit (Btu) (thermochemical)	1.054 350	$\times 10^{3}$	joule (J)
foot-pound-force (ft lbf)	1.355 818		joule (J)
calorie (cal) (thermochemical)	4.184		joule (J)
Pressure			
atmosphere (atm)	1.013 250	$\times 10^{5}$	pascal (Pa)
pound force per square inch (psi)	6.984 757	$\times 10^{3}$	pascal (Pa)
Temperature			
degree Fahrenheit (°F)	[T(°F) − 32]/1.8		degree Celsius (°C)
degree Fahrenheit (°F)	[T(°F) + 459.67]/1.8		kelvin (K)
Radiation			
curie (Ci) [activity of radionuclides]	3.7	$\times 10^{10}$	per second (s^{-1}) [becquerel (Bq)]
roentgen (R) [air exposure]	2.579 760	$\times 10^{-4}$	coulomb per kilogram (C kg^{-1})
rad [absorbed dose]	1	$\times 10^{-2}$	joule per kilogram (J kg^{-1}) [gray (Gy)]
rem [equivalent and effective dose]	1	$\times 10^{-2}$	joule per kilogram (J kg^{-1}) [sievert (Sv)]

*Specific details regarding the implementation of SI units may be viewed at http://www.bipm.org/en/si/.
†Multiply the U.S. customary unit by the factor to get the international unit. Divide the international unit by the factor to get the U.S. customary unit.

FINAL REPORTS

PI: Yong P. Chen (yongchen@purdue.edu)

Address/Institution:

Dept. of Physics, 525 Northwestern Ave

Purdue University, West Lafayette IN 47907

Grant#: HDTRA1-09-1-0047

Young Investigator Award

“Interaction of Radiation with Graphene Based Nanomaterials”

11/2013

Annual Reports

DTRA requires award recipients to report progress in the following categories:

- *Accomplishments: What was done? What was learned? See Required Reporting Category 1,*
- *Products: What has the project produced? See Required Reporting Category 2,*
- *Participants & Other Collaborating Organizations: Who has been involved? See Required Reporting Category 3,*
- *Impact: See Required Reporting Category 4, and*
- *Changes/Problems: See Required Reporting Category 5.*

DTRA requires the sub-elements in each of these categories be addressed, as detailed in the table below. A detailed description of what is expected in each section is included in this document as noted in the bullets above.

Note that the Principal Investigator (PI) should become familiar with the layout of the web-based interface for the submission of this information as it is no longer submission of a single document. The web-based interface includes a series of text boxes and drop down menus which must be completed and supports the upload of additional information (e.g., data, graphs, etc).

Invention Reports

DTRA requires that invention reports be filed annually using DD Form 882 Reporting of Inventions and Subcontracts in accordance with the published instructions for the form if the awardee has a reportable event. DTRA does not require negative reports to be submitted to fulfill this annual requirement; negative outcomes can be covered in the annual report. If the awardee has a reportable event, the DD Form 882 should be uploaded to the web-based interface as well as submitted through the channels as detailed in the current terms and conditions of the award. The DD Form 882 Invention Report form may be downloaded at: www.dtic.mil/whs/directives/infomgt/forms/eforms/dd0882.pdf

Quad Charts

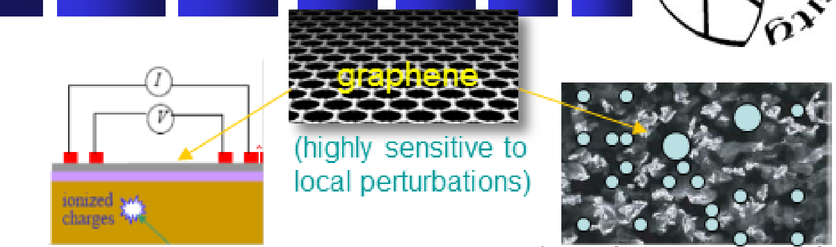
DTRA requests that an updated quad chart for the project be submitted annually. The quad chart should conform to the format provided online at www.dtrasubmission.net/portal in the Document Library in MS PowerPoint format. The quad chart must be presented on 1 page. The quad chart must not contain any proprietary data or markings. The quad chart must be provided in landscape layout. Quad charts may be submitted to the web-based interface as a MS PowerPoint file.

To be submitted as a separate file as well.

Interaction of Radiation with Graphene-based Nanomaterials, Dr. Yong P. Chen, Purdue University, Grant# HDTRA1-09-1-0047

Objective:
To understand how ionizing radiation interact with nano-materials/structures based on graphene, leading to detectable responses.

Method:
•Graphene-based nanomaterials have great potentials for radiation detection.
•Need to understand how radiation interacts with such materials. Investigated systematically radiation effect with such materials by combined electronic transport, Raman spectroscopy, and material microscopy measurements.



(graphene on radiation-absorbing semiconductor substrate)

(graphene composite)
: semiconductor nanoparticles

How do ionizing radiations interact with such graphene based nanostructured materials and change the local physical or chemical environment in a detectable way?

Status of effort: Investigated photoconductivity of graphene and graphene-nanoparticle hybrid. Studied defects in graphene due to irradiation. Investigated effect of X-ray/gamma on graphene undoped substrate

Personnel Supported: 1 faculty (Y. P. Chen), 1 post-Doc, Several graduate/undergraduate students supported by and/or associated with the research effort.

Publications & Meetings: 3 Journal paper, 3 symposia publications; 1 invited talk, 1 contributed talk

Major goals/milestones:
•Study gamma/neutron effect on graphene on BN
•Study radiation effect on graphene-NP hybrid
•Fabricate neutron sensors by combining graphene photodetector with scintillators.

Funding Profile ($100K/Yr)
Year 01(7/1/11-6/30/12); Year 02 (7/1/12-6/30/13)

Contact information: Prof. Yong P. Chen
Email : yongchen@purdue.edu
Phone: 765-494-0947

Metric Summaries Spreadsheet Table

(copied here, to be submitted as a separate file as well)

All data submitted here is for the reporting period 9/1/2012 to 9/1/2013. **DO NOT** include information outside this reporting range unless it was not reported in a previous years report.

	Personnel									**Publications**								
Award #:[1]	**PIs/Co-PIs** [2]	**Post-Doctoral Fellows** [2,3]		**Graduate Students** [2,3]		**Undergraduate Students** [2,3]		**Research Technicians** [2]	**PI's Hirsch Index** [4]	**Year**	**Publications (Peer-Reviewed Journals)** [5]		**Publications (Proceedings)** [6]	**Publications (Books)** [7]	**Publications (Theses)** [8]		**Publications (Other)** [9]	**Invention Disclosures** [10]
		U.S. + non-U.S.	**U.S.**	**U.S. + non-U.S.**	**U.S.**	**U.S. + non-U.S.**	**U.S.**				**Published**	**Submitted, in review, accepted, or in press**			**Ph.D.**	**Masters**		
HDTRA1-09-1-0047	1	1	0	3	1	0	0	0	27	**2012 (after 9/1/11)**	0	0	2	0	0	0	0	0
										2013	3	0	1	0	0	0	0	0

[1] Enter Award #, starts with "HDTRA"

[2] Enter number of U.S. + non-U.S. personnel working on this award
[3] Enter number of U.S. personnel working on this award
[4] Enter PI's Hirsch Index

[5] Enter total number of peer-reviewed publications for this award (includes only published (print and online)) for this reporting period
[5] Include additional peer reviewed pubs that are "submitted", "in review", "accepted", or "in press"
[6] Enter number of non-peer reviewed conference proceedings articles for this award for this reporting period
[7] Enter number of published books or chapter of books for this reporting period
[8] Enter number of Ph.D. dissertations and Masters Theses for this reporting period
[9] Enter number of other publications for this reporting period
[10] Enter number of invention disclosures

Table: Data elements and input methods

Main Category	Sub-Elements	Input	Att.
Accomplishments	What are the major goals of the project?	Reported individually; free text	Yes
	What was accomplished under these goals?		
	What opportunities for training and professional development has the project provided?		
	How have the results been disseminated to communities of interest?		
	What do you plan to do in the next reporting period to accomplish these goals?		
Products	Publications, conference papers, and presentations	Reported individually; survey and free text	Yes
	Websites or other internet sites		
	Technologies or techniques		
	Inventions, patent applications, and/or licenses		
	Other products, including awards		
Participants & Other Collaborating Organizations	What individuals have worked on the project?	Survey and free text	No
	What other organizations have been involved as partners?	Reported individually; free text	No
	How have other collaborators or contacts been involved?		
Impact	What is the impact on the principle discipline(s) of the project?	Reported Individually; survey and free text	No
	What is the impact on other disciplines?		
	What is the impact on the development of human resources?		
	What is the impact on physical, institutional, and information resources that form infrastructure?		
	What is the impact on technology transfer?		
	What is the impact on society beyond science and technology?		
	What dollar amount of the award's budget is being spent in foreign country(ies)?		
Changes/ Problems	Changes in approach and reasons for change	Free Text	No
	Actual or anticipated problems or delays and actions or plans to resolve them		
	Changes that have a significant impact on expenditures		
	Significant changes in use or care of human subjects, vertebrate animals, and/or biohazards		
	Change of primary performance site location from that originally proposed		

Mandatory Reporting Category 1: Accomplishments

Addressing accomplishments, specifically what was done and what was learned, allows DTRA to assess the progress that has been made during the reporting period. In all cases, if there is nothing significant to report during this reporting period, the awardee shall state "Nothing to Report."

In the Accomplishments Section, the PI must address the following five (5) questions:

1. *What are the major goals of the project? List the major goals and objectives of the project. In cases where the goals or objectives are different from the original plan or the previous reporting period, provide the updated goals and objectives and a discussion of the reason for the change.*

   1) To understand the basic science about how ionizing radiation (gamma rays, neutrons) and associated charged particles interact with nano-materials/structures based on graphene, which has shown extreme sensitivity to local environmental perturbations.

   2) To develop scientific foundation that may lead to graphene based radiation sensors with sensitivity & energy resolution in par or exceeding HPGe sensors and operating at close to room temperature for long distance fissile material detection.

2. *What was accomplished under these goals? For this reporting period describe: 1) major activities; 2) specific objectives; 3) significant results, including major findings, developments, or conclusions (both positive and negative); and 4) key outcomes or other achievements.*

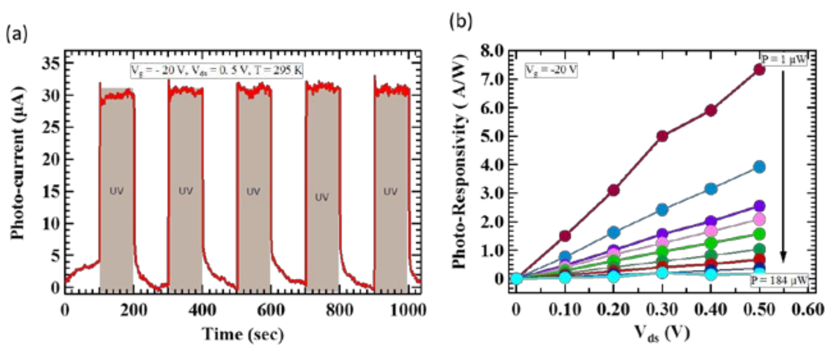


Figure 1. (a) Photocurrent response as a graphene FET on gated silicon carbide (b) Photoresponsivity versus source-drain voltage (V_{ds}) for various light powers.

A set of major accomplishments of this project is the study of photo and radiation responses of a variety of graphene-based hybrid materials, especially graphene-semiconductor hybrids. Recent main achievements include:

1) We fabricated graphene field effect transistors (GFETs) using undoped SiC substrate (undoped semiconductor) and studied the photoresponse (photoconductivity) of such GEFTs. Recently, graphene based photodetectors have attracted a lot of attentions due to its extemly wide absoption range, and high carrier moility. A varity of graphene based photodetectors have been reported which can be either fabricated from pure monolayer graphene or graphene-nanomaterials hybrids. Here, we demonstrate a simple approach for fabricating graphene photodetectors with high

responsively and low response time at room temperature. Single layer graphene is obtained by micromechanical exfoliation and transferred onto SiC substrate by standard polymer assistant method. The electrical contacts are fabricated using standard electron beam lithography followed by metal (Cr/Au) deposition and liftoff. Without light illumination, the effect of gate voltage on the device is very small; however, field effect response of the device is enhanced significantly under laser illumination. We found that photoresponse is highly reproducible (Fig1a), photocurrent and photoresponsivity increase with increasing the source-drain voltage and laser power (Fig1b). The maximum photoresponsivity of our device at room temperature is 7.3 A/W at source-drain voltage of -0.5 V for laser power of 1 μW. We propose that the field effect photoresponse in our devices relies on the high sensitivity of the conductivity of graphene to the local change of the electric field that can result from photo-excited carriers produced in the underlying gated SiC substrate. Our work presented here will open a new pathway for future graphene based high-performance optoelectronic devices.

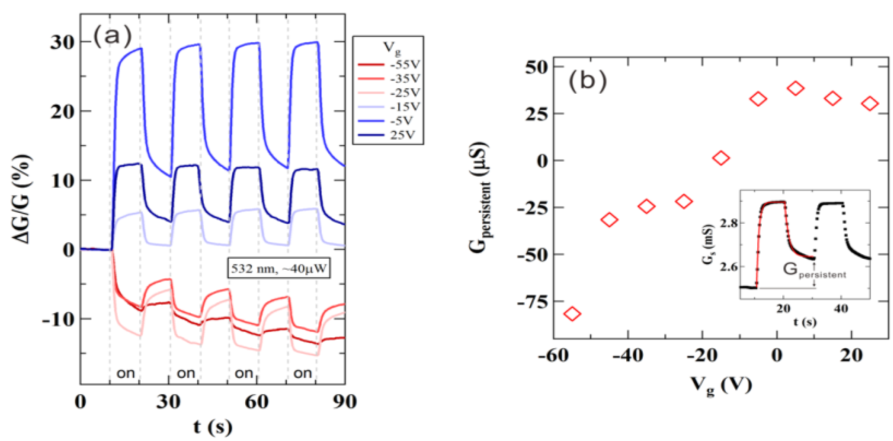


Figure 2. (a) Transient photoresponse and (b) Persistent photocurrent of graphene-semiconductor hybrid.

2) We have studied the photoresponse (photoconductivity) of a photodetectors based on graphene-semiconductor hybrid. Hybrid devices combining two or more nanomaterials are of interest because of the potential for improving their individual properties and generating new functionalities. We also synthesized a hybrid material consisting of CVD graphene (grown by chemical vapor deposition) coated with semiconductor (CdSe) quantum dots/nanoparticles. Photosensitive hybrid devices made of CVD graphene decorated with cadmium selenide quantum dots (CdSe QDs) have been explored in this study. We have measured both the transient (Fig.2a) and long-term (persistent) Fig. 2(c) photoelectrical responses, which are both gate-tunable and show either positive or negative photoconductivities, in this type of devices. We find that the decay of long-term photoelectrical response is slow, while thermal treatment can suppress the persistent photoconductivity. Using the ambipolar field effect of the graphene, we have also measured the charge transfer from CdSe to graphene in the devices subjecting to different ligands and conditions. Our graphene-CdSe QDs hybrid devices showing tunable photoelectrical performances will give insights on the photoelectric responses of graphene-semiconductor hybrid, as well as may find applications in optoelectronics and photovoltaics.

3) We continued our studies of the transient interactions of photons (visible, X-rays and gamma rays) with graphene field effect transistors (GFET) made from exfoliated, epitaxial, and CVD graphene on various absorber substrates such as Si, SiC, and GaAs, CdTe, and the potential of GFETs to sense ionizing radiation with high sensitivity, low noise, and room temperature operation has been experimentally demonstrated. Response of GFETs to X-rays has been measured both at cryogenic and room temperatures. SiC absorber based GFETs have shown promising results for detection of ionizing radiation (both X-rays and gamma rays) at room temperature. Room temperature responses to light and X-rays are also observed for graphene on CdTe and on GaAs/AlGaAs heterostructures (containing a 2D electron quantum well).

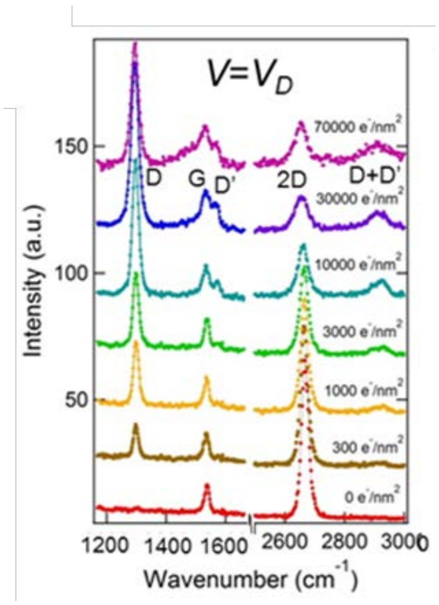


Figure 3.: Raman spectra of graphene at its charge-neutral point for different dosages of irradiation.

4) We also continued our studies of how electron beam irradiation interacts directly with graphene in the effect of generating defects in graphene and changing graphene properties. We directly investigate the dependence of graphene's Raman characteristics on both carrier density and the level of disorder in a graphene sample with disorder created by electron-beam irradiation (Fig 3).We have demonstrated that both disorder and n_{FE} affect a number of Raman peak parameters, including peak position, width and intensity for the D, G and 2D modes. We measured these effects and have concluded that increased n_{FE} in graphene causes the removal of the Kohn anomaly and decreases phonon scattering, while increased disorder reduces electron-phonon coupling and increases phonon scattering. Our results are valuable for understanding Raman spectra and electron-phonon physics in doped and disordered graphene. This study provides us valuable information about graphene properties under irradiation, which may help to design graphene based radiation sensors.

5) In other collaborative works, we also combined our CVD graphene with other semiconducting substrate (e.g. silicon carbide) to investigate the effect of substrate in photoresponse measurement. Besides, we have continued to explore the radiation interaction in graphene with integrated plasmonic metal nanostructures. We successfully improved the operation wavelength of the graphene-metal plasmonic hybrid devices from mid-IR to near-IR by using dolmen structure design. An effective electrical control of the plasmonic resonance frequency was demonstrated with strong ion liquid gating. Furthermore, we investigate other possibilities of CVD graphene. We studied the ultrafast hot charge carrier dynamics in CVD graphene, and also examined the stability of CVD graphene in biological environments. These studies may reveal novel mechanisms in the interaction of photon and graphene. The understanding of these properties could lead a better control in radiation interaction on graphene and exploit new device design for applications.

3. *What opportunities for training and professional development has the project provided? Describe opportunities for training and professional development provided to anyone who worked on the project or anyone who was involved in the activities supported by the project.*

   - *"Training" activities are those in which individuals with advanced professional skills and experience assist others in attaining greater proficiency. Training activities may include, for example, courses or one-on-one work with a mentor.*
   - *"Professional development" activities result in increased knowledge or skill in one's area of expertise and may include workshops, conferences, seminars, study groups, and individual study. Include participation in conferences, workshops, and seminars not listed under major activities.*

   1) Students and postdocs i) are mentored by the PI in their research; ii) are supervised through their lab experiments and equipment use by more senior members of the group and staff at Purdue Birck Nanotechnology Center; iii) interact with each other and with other research groups to share their experience and develop further understanding of the phenomena; iv) use facilities at some nationwide research labs; v) work with companies to resolve technical problems they are confronted with along their research and for further development of the infrastructure / facilities needed for their research

   2) Students and postdocs are offered the opportunity to attend conferences where they can present their work, gain deeper insight into the field, and exchange information with other researchers in the field.

   3) "Carbon Nanophysics" course is taught by the PI at Purdue. PI also gave several lectures for undergraduate students on "carbon nanoscience & nanotechnologies" where he discussed the graphene based radiation detector as one emerging application and raised the awareness of need for more research and development in radiation detection.

4. *How have the results been disseminated to communities of interest? Describe how the results have been disseminated to communities of interest. Include any outreach activities that have been undertaken to reach members of communities who are not usually aware of these research activities, for the purpose of enhancing public understanding and increasing interest in learning and careers in science, technology, and the humanities.*

   Via publications and presentations

5. *What do you plan to do during the next reporting period to accomplish the goals? If there are no changes to the DTRA-approved plan for this effort, state "No Change." In cases where there are anticipated changes, describe briefly what you plan to do during the next reporting period to accomplish the goals and objectives.*

   No change

Mandatory Reporting Category 2: Products

The products from an effort demonstrate the excellence and significance of the research and the efficacy with which the results are being communicated to colleagues, potential users, and the public. Publications are the characteristic product of research. Many projects (though not all) may develop products other than publications. In all cases, if there is nothing significant to report during this reporting period, the awardee shall state "Nothing to Report."

In the Products Section, the PI must address the following five (5) product types:

1. *Publications, conference papers, and presentations: Report ONLY the major publication(s) resulting from the work under this award DURING THE REPORTING PERIOD. There is no restriction on the number.*

   - *Journal publications. List peer reviewed articles or papers appearing in scientific, technical, or professional journals. Include any peer reviewed publication in the periodically published proceedings of a scientific society, a conference, or the like. A publication in the proceedings of a one-time conference, not part of a series, should be reported under "Books, or other non-periodical, one-time publications."Identify for each publication: Author(s), title, journal, volume, year, page numbers, status of publication, and acknowledgement of federal support. Provide the impact factor.*

1) Biddut K. Sarker, Isaac Childres, Edward Cazalas, Igor Jovanovic, and Yong P. Chen, "Graphene Field Effect Phototransistors with High and Tunable Photoresponsivity", **In Preparation** (2013), Acknowledgement: NSF (0833689-ECCS), DHS (2009-DN-077-15 ARI036-02), DTRA (HDTRA1-09-1-0047)

2) A. Patil, G. Lopez, O. Koybasi, I. Childres1, E. Cazalas, M. Foxe, B. K. Sarker, T-F. Chung, T. Shen, M. Bolen, M. Capano, P.D. Ye, I. Jovanovic, and Y. P. Chen, "Graphene Transistors as X-ray Sensors", **In Preparation** (2013); Acknowledgement: NSF (0833689-ECCS), DHS (2009-DN-077-15 ARI036-02), DTRA (HDTRA1-09-1-0047)

3) Isaac Childres, Luis A. Jauregui, Yong P. Chen, "Raman spectra and electron-phonon coupling in disordered graphene with gate-tunable doping, **In Preparation** (2013), Acknowledgement: NSF (0833689-ECCS), DHS (2009-DN-077-15 ARI036-02), DTRA (HDTRA1-09-1-0047)

4) Edward Cazalas, Isaac Childres, Amanda Majcher, Ting-Fung Chung, Yong P. Chen and Igor Jovanovic, "Hysteretic Response of Chemical Vapor Deposition Graphene Field Effect Transistors on SiC Substrates", **Applied Physics Letters** 103, 053123 (2013); Acknowledgement : DHS, NSF, NSF-ARI (2009-DN-077-ARI036-02), DTRA; Impact factor: 3.794

5) Rui He*, Ting-Fung Chung*, Conor Delaney, Courtney Keiser, Luis A. Jauregui, Paul M. Shand, C. C. Chancey, Yanan Wang, Jiming Bao, and Yong P. Chen (*equal contribution), "Observation of Low Energy Raman Modes in Twisted Bilayer Graphene" , **Nano Letters** 13,

3594 (2013); Acknowledgement: Pre-Tenure Summer Fellowship Award from the University of Northern Iowa, American Chemical Society Petroleum Research Fund (Grant 53401-UNI10), SOAR award, NSF Grant DMR 1206530, NSF(ECCS-1240510 and DMR-0907336), Robert A Welch Foundation (E-1728), DTRA; Impact factor: 13.025

6)Ting-fung Chung, Tian Shen, Helin Cao, Luis A. Jauregui, Wei Wu, Qingkai Yu, David Newell and Yong P. Chen,"Synthetic Graphene Grown by Chemical Vapor Deposition on Copper Foils" (invited review paper), **International Journal of Modern Physics B** 27, 1341002 (2013) ; Acknowledgement: NSF, NIST and DTRA ; Impact factor: 0.358

7) Igor Jovanovic, Edward Cazalas, Isaac Childres, Amol Patil, Ozhan Koybasi, and Yong P. Chen, "Graphene field effect transistor-based detectors for detection of ionizing radiation", Proc. of 3rd International Conference on the Advancements in Nuclear Instrumentation Measurement Methods and their Applications (ANIMMA), Marseille, France (2013);DOI:10.1109/ANIMMA.2013.6727932; ; Acknowledgement: DHS (2009-DN-077-AR1036- 02), DOD-DTRA (HDTRA 1-09-1-0047)

8) Ozhan Koybasi, Isaac Childres, Igor Jovanovic and Yong P. Chen, “Design and Simulation of a Graphene DEPFET Detector”, 2012 IEEE Nuclear Science Symposium and Medical Imaging Conference Record, 4249 (2012); Acknowledgement:DHS (2009-DN-077- AR 1036-02) and DOD-DTRA (HDTRA1-09-1-0047)

9) Ozhan Koybasi, Isaac Childres, Igor Jovanovic and Yong P. Chen, "Graphene field effect transistor as a radiation and photodetector" (invited paper), 2012 Defense Science Symposium Micro- and Nanotechnology Sensors, Systems, and Applications IV, Baltimore, MD; Proc. SPIE 8373, 83730H (2012); Acknowledgement: DHS (2009-DN-077-ARI036- 02), DTRA

- *Books or other non-periodical, one-time publications. Report any book, monograph, dissertation, abstract, or the like published as or in a separate publication, rather than a periodical or series. Include any significant publication in the proceedings of a one-time conference or in the report of a one-time study, commission, or the like. Identify for each one-time publication: Author(s), title, editor, title of collection (if applicable), bibliographic information, year, type of publication (book, thesis or dissertation, other), status of publication (published, accepted, awaiting publication, submitted, under review, other), and acknowledgement of federal support.*

  None

- *Other publications, conference papers and presentations. Identify any other publication, conference papers, and or presentations not reported above. Specify the status of the publication as noted above.*

  Conference Presentations:

  1) Yong Chen (invited)” Material Research Society (MRS) Spring Meeting 2013, Symposium P “Graphene and Related Carbon Nanomaterials”, San Francisco CA (04/2013)

2) N. K. Emani, T. F. Chung, L. Prokopeva, A. V. Kildishev, Y. P. Chen, and A. Boltasseva, Tuning Fano resonances with graphene, CLEO: 2013 Technical digest, Optical Society of America (2013) paper CW3O.4

Website(s) or other Internet site(s) List the URL for any Internet site(s) that disseminates the results of the research activities. A short description of each site should be provided. It is not necessary to include the publications already specified in this section.

Quantum Matter and Devices Lab at Purdue University:

http://www.physics.purdue.edu/quantum/

2. *Technologies or techniques. Identify technologies or techniques that have resulted from the research activities. Describe the technologies or techniques and how they are being shared. NOTE: DTRA does not anticipate that ANY basic or fundamental research award will produce technologies.*

   None

3. *Inventions, patent applications, and/or licenses. Identify inventions, patent applications with date, and/or licenses that have resulted from the research. Submission of this information as part of report is not a substitute for any other invention reporting required under the terms and conditions of an award.*

   None

4. *Other products. Identify any other significant products that were developed under this project. Describe the product and how it is being shared.*

   None

Mandatory Reporting Category 3: Participants & Other Collaborating Organizations

Providing information on the project participants and collaborating organizations allows an assessment of performance in promoting partnerships and collaborations. In all cases, if there is nothing significant to report during this reporting period, the awardee shall state "Nothing to Report."

In the Participants & Other Collaborating Organizations Section, the PI must address the following three (3) questions:

1. *What individuals have worked on the project? Provide the following information for: 1) principal investigator(s)/project director(s) (PIs/PDs); and 2) each person who has worked at least one person month per year on the project during the reporting period, regardless of the source of compensation (a person month equals approximately 160 hours of effort).*

   - *Identify the role the person played in the project. Indicate the nearest whole person month that the individual worked on the project. Show the most senior role in which the person has worked on the project for any significant length of time.*

   - *Describe how this person contributed to the project and with what funding support.*

- *Identify whether this person is collaborating internationally. Specifically, is the person collaborating with an individual located in a foreign country and has the person traveled to the foreign country as part of that collaboration, and if so, the duration of stay? The foreign country(ies) should be identified.*

  1) Prof. Yong P. Chen (PI)

  2) Dr. Biddut K. Sarker (Postdoctoral Research Associate): 01/2013-present: Graphene based photodetectors and radiation sensors, synthesized graphene by chemical vapor deposition and transferred CVD graphene on various substrates for photodetectors and radiation detectors, fabrication of photodetectors and radiation detectors, performing various experimental tests of effect of light with various wavelengths, X-rays, gamma-rays on graphene & graphene devices.

  2) Jack T-F. Cheng (Grad); 09/2010-present; Graphene-semiconductor hybrids (developed synthesis of large size graphene by chemical vapor deposition and transferred CVD graphene on various semiconductor substrates for radiation sensing experiments; synthesized CVD graphene-CdSe quantum dot hybrids and performed experiments studying their photoconductivity responses)

  3) Wonjun Park (Grad); 01/2010-Present; Graphene-based nanocomposites (developed synthesis of graphene composite and graphene-oxide composite, and procedures of adding semiconductor nanoparticle fillings; performed experiments to characterize such graphene composites and studied their response to light and X-ray photons)

  4) Isaac Childres (Grad), mostly funded by DHS-ARI program, 01/2008-Present; Radiation effects on graphene based materials and sensors (main contributions include device fabrication and characterization of effects of electron beam and oxygen plasma irradiation on graphene and graphene FETs, performing various experimental tests of effect of light, X-rays, gamma-rays and neutrons on graphene & graphene FET)

2. *What other organizations have been involved as partners? Describe partner organizations – academic institutions, other nonprofits, industrial or commercial firms, state or local governments, schools or school systems, or other organizations (foreign or domestic) – that have been involved with the project.*

   Pennsylvania State University, University of Houston/Texas State University, University of Northern Iowa, NSF/DHS-ARI, NSF, SRC/NRI, NIST

3. *Have other collaborators or contacts been involved? Some significant collaborators or contacts within the recipient's organization may not be covered by "What people have worked on the project?" Likewise, some significant collaborators or contacts outside the recipient's organization may not be covered under "What other organizations have been involved as partners?" It is likely that many recipients will have no other collaborators or contacts to report.*

   Igor Jovanovic (Pennsylvania State University); Peide Ye & Mike Capano (Purdue ECE); Qingkai Yu (U. Houston/Texas State U); Xiulin Ruan (Purdue Mechanical Engineering), Gary Cheng (Purdue Industrial Engineering), Alexandra Boltasseva (Purdue Electrical Engineering), Rui He (University of Northern Iowa)

Mandatory Reporting Category 4: Impact

Information on the impact of the research demonstrates how the investment increases the scientific body of knowledge, enlarges the pool of people trained to develop that knowledge and techniques or put it to use, and improves the physical, institutional, and information resources that enable those people to get their training and perform their functions. In all cases, if there is nothing significant to report during this reporting period, the awardee shall state "Nothing to Report."

In the Impact Section, the PI must address the following seven (7) questions:

1. *What is the impact on the development of the principal discipline(s) of the project? Describe how findings, results, techniques that were developed or extended, or other products from the project made an impact or are likely to make an impact on the base of knowledge, theory, and research and/or pedagogical methods in the principal disciplinary field(s) of the project. Summarize using language that an intelligent lay audience can understand (Scientific American style). Include in response the PI's Hirsch Index.*

   This project has advanced understanding of the basic mechanisms and scientific knowledge about how ionizing radiation (gamma rays, neutrons) and associated charged particles interact with nano-materials/structures based on graphene, which has shown extreme sensitivity to local environmental perturbations. Developing such a scientific & material foundation that may lead to graphene based radiation sensors outperforming current sensors in various aspects and operating at close to room T for long distance fissile material detection.

2. *What is the impact on other disciplines? Describe how the findings, results, or techniques that were developed or improved, or other products from the project made an impact or are likely to make an impact on other disciplines.*

   Work in this project also helped advance the synthesis of various high quality graphene based materials (including large size CVD graphene, graphene composites, and their hybrids with semiconductors). These materials developed could find many other applications (electronic, optical, chemical, mechanical etc.) employing the unique properties of graphene. This project also helped us reveal new ways graphene based materials and devices may interact with charges and photons and may enable new applications in developing a broad range of sensors and optoelectronic devices.

3. *What is the impact on the development of human resources? Describe how the project made an impact or is likely to make an impact on human resource development in science, engineering, and technology. For example, how has the project:*

   - *Provided opportunities for research and teaching in the relevant fields;*
   - *Led to honors, degrees, and awards received during the award period;*
   - *Improved the performance, skills, or attitudes of members of underrepresented groups that will improve their access to or retention in research, teaching, or other related professions;*
   - *Developed and disseminated new educational materials or provided scholarships; specifically list class name, curriculum level and dates of any counter weapons of mass destruction (WMD) classes taught by the PI or Co-PI if applicable; or*

- *Provided exposure to science and technology for practitioners, teachers, young people, or other members of the public?*

  This work has impacted & benefited the career of many former students/postdocs that participated in the research. Many now work in areas directly related to or benefiting national security and radiation detection/applications.

  Gabriel Lopez (received MSEE degree in 2010) is now at Sandia National Lab working on radiation detection and other national security related research. He also was a finalist for a DOD SMART fellowship.

  Amol Patil (previous postdoc) is now at Canberra, a leading radiation detection company the the US.

  Romana Jalillian (previous postdoc, female) has co-started a small company (NaugaNeedles) on nanotechnology.

  Ozhan Koybasi (previous postdoc) is now in SINTEF, largest independent research organisation in Scandinavia.

4. *What is the impact on physical, institutional, and information resources that form infrastructure? Describe ways, if any, in which the project made an impact, or is likely to make an impact, on physical, institutional, and information resources that form infrastructure, including:*

   - *Physical resources such as facilities, laboratories, or instruments;*
   - *Institutional resources (such as establishment or sustenance of societies or organizations); or*
   - *Information resources, electronic means for accessing such resources or for scientific communication, or the like.*

   This project has helped setup or improve import experimental facilities at Purdue both for synthesizing high quality graphene related materials (graphene grown by CVD, and graphene composite), and for testing radiation effect on nanomaterials and nanodevices. These facilities have become important resources and have enabled other researches and helped initiate various new applications and collaborations both within and beyond Purdue.

5. *What is the impact on technology transfer? Describe ways in which the project made an impact, or is likely to make an impact, on commercial technology or public use, including:*

   - *Transfer of results to entities in government or industry; and*
   - *Adoption of new practices.*

   None to report yet.

6. *What is the impact on society beyond science and technology? Describe how results from the project made an impact, or are likely to make an impact, beyond the bounds of science, engineering, and the academic world on areas such as:*

   - *Improving public knowledge, attitudes, skills, and abilities;*
   - *Changing behavior, practices, decision making, policies (including regulatory policies), or social actions; or*
   - *Improving social, economic, civic, or environmental conditions.*

Potential societal benefits include national security (better safeguarding of nuclear materials and counterterrorism), as well as other benefits associated with advances in radiation sciences including health care (eg. radiation medicine). We also helped raise the public awareness of these relevant issues through publications and talks given.

7. *What dollar amount of the award's budget is being spent in foreign country(ies)? Describe what percentage of the award's budget is being spent in foreign country(ies). If more than one foreign country, identify the distribution between the foreign countries.*

   None.

Mandatory Reporting Category 5: Changes/Problems

The PI is reminded that the award may contain specific instructions regarding significant changes in a project or its direction. See the Terms and Conditions of the award document for instructions regarding the submission of these requests. In all cases, if there is nothing significant to report during this reporting period, the awardee shall state "Nothing to Report."

In the Changes/Problems Section, the PI must address the following five (5) issues:

1. *Changes in approach and reasons for change. Describe any changes in approach during the reporting period and reasons for these changes.*

   No change

2. *Actual or anticipated problems or delays and actions or plans to resolve them. Describe problems or delays encountered during the reporting period and actions or plans to resolve them.*

   None

3. *Changes that have a significant impact on expenditures. Describe changes during the reporting period that may have a significant impact on expenditures, e.g. delays in hiring staff or favorable developments that enable meeting objectives at less cost than anticipated.*

   None to report

4. *Significant changes in use or care of human subjects, vertebrate animals, and/or biohazards. Describe significant deviations, unexpected outcomes, or changes in approved protocols for the use or care of human subjects, vertebrate animals, and/or biohazards during the reporting period. If required, were these changes approved by the applicable institution committee and reported to the agency? Also specify the applicable Institutional Review Board/Institutional Animal Care and Use Committee approval dates.*

   Not applicable

5. *Change of primary performance site location from that originally proposed. Identify any change to the primary performance site location identified in the proposal, as originally submitted.*

   No change.

DEPARTMENT OF DEFENSE

DEFENSE THREAT REDUCTION
AGENCY
8725 JOHN J. KINGMAN ROAD
STOP 6201
FORT BELVOIR, VA 22060
ATTN: D. PETERSEN

DEFENSE TECHNICAL
INFORMATION CENTER
8725 JOHN J. KINGMAN ROAD,
SUITE 0944
FT. BELVOIR, VA 22060-6201
ATTN: DTIC/OCA

DEPARTMENT OF DEFENSE CONTRACTORS

QUANTERION SOLUTIONS, INC.
1680 TEXAS STREET, SE
KIRTLAND AFB, NM 87117-5669
ATTN: DTRIAC